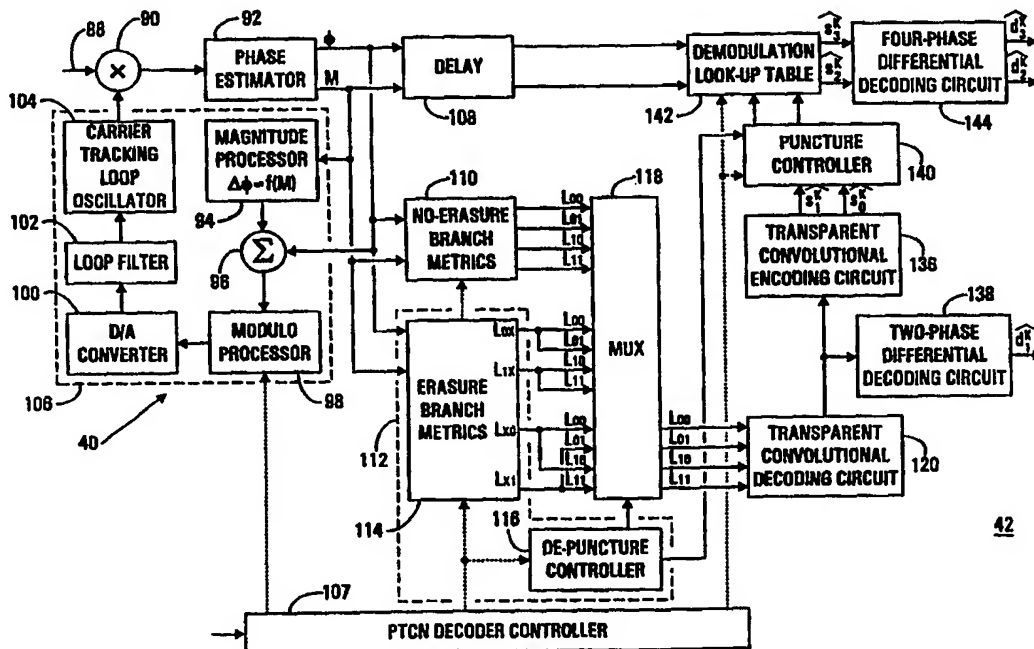


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(54) Title: DEMODULATION SYSTEM AND METHOD THEREFOR



(57) Abstract

A digital communication system (20) includes a decoder (42) for decoding a punctured convolutionally encoded data stream from an encoder (28). The decoder includes a phase estimator (92) for generating phase estimate values, a depuncture circuit (112) for periodically generating erasure values responsive to the phase estimate values, and a convolutional decoder for decoding the erasure values.

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DEMODULATION SYSTEM AND METHOD THEREFOR

TECHNICAL FIELD

The present invention relates generally to the field of digital communications.

- 5 More specifically, the present invention relates to pragmatic trellis-coded demodulators for digital communications.

BACKGROUND ART

- Data communications systems face a wide range of performance demands. These
10 demands include bandwidth efficiency, power efficiency, signal-to-noise (SNR) efficiency, and robustness. Bandwidth efficiency refers to successfully communicating data using as little bandwidth as possible. Power efficiency refers to transmitting as much energy per bit as possible for a given amount of consumed power. SNR efficiency refers to successfully communicating data using as little energy per bit as possible.
15 Robustness refers to tolerating a variety of transmission channels characteristics. While conventional system designs often attempt to meet these demands independently of one another, they are interrelated.

- Phase shift keying (PSK) represents a class of modulations that do a good job of meeting power efficiency, SNR efficiency, and some robustness demands. Power
20 efficiency is achieved because PSK modulations convey data using phase, but not amplitude, relationships between quadrature components of a digital communication transmission signal. Since amplitude is not modulated, highly efficient class-C amplifiers may be employed in transmitters. SNR efficiency is achieved by using any of a wide variety of conventional coding schemes. One popular coding scheme is
25 concatenated coding. Typically, a block code, such as a Reed-Solomon code, is applied as an outer code, and a convolutional code, such as the well known K=7, rate 1/2 "Viterbi" convolutional code, is applied as an inner code.

- The symbol data are conveyed through the phase (PSK) or amplitude and phase (APSK) relationships between the quadrature components of the transmit signal. The
30 PSK or APSK mapping causes the phase constellation to be perturbed more by the primary modulation than by the secondary modulation.

Pragmatic trellis-coded modulation (PTCM) employs primary and secondary modulation schemes. A first set of information bits being communicated is processed by the primary modulation scheme, and a second set of communicated information bits is processed by the secondary modulation scheme. Differential encoding may optionally be applied independently to the first and second sets of information bits to help a receiving decoder resolve rotational ambiguities. The secondary modulation scheme encodes the second set of information bits, which may be optionally differentially encoded with a strong error detection and correction code, such as the above-mentioned Viterbi encoding. The primary modulation scheme need not encode its subset of the information bits, other than the optional differential encoding. The resulting first and second sets of bits are then concurrently PSK or APSK mapped to generate quadrature components of a transmit signal.

PTCM has become popular because it allows a single convolutional encoder and decoder to achieve respectable coding gains for a wide range of bandwidth efficiencies (e.g. 1–6 b/s/Hz) and a wide range of higher order coding applications, such as 8-PSK, 16-PSK, 16-QAM, 32-QAM, etc. Accordingly, PTCM addresses both SNR efficiency and robustness. PTCM may be used within a concatenated coding scheme. For lower order coding applications, such as QPSK or BPSK, PTCM offers no advantage because quadrature, complex communication signals provide two independent dimensions (i.e. I and Q) per unit baud interval with which to convey two or fewer symbols per unit interval. PTCM solves some of the robustness demands because a wide range of coding applications can be accommodated with a single set of hardware.

Generally, PTCM conveys “coded” bits with “uncoded” bits during each unit interval. In other words, each phase point of a phase-point constellation is defined by both coded and uncoded bits. The coded bits receive convolutional encoding and the uncoded bits do not. Regardless of modulation order or type, the convolutional coding parameters are the same for any of a wide range of coding applications.

Unfortunately, the PSK class of modulations exhibit relatively poor bandwidth efficiency and are conventionally unable to resolve some robustness demands, such as rotational invariance. Accordingly, digital communication systems occasionally look to

amplitude phase shift keying (APSK) modulation to achieve bandwidth efficiency over PSK modulation.

APSK modulation achieves performance improvements over an otherwise equivalently ordered PSK modulation. APSK modulations convey data using both
5 amplitude and phase relationships between quadrature components of a digital communication transmission signal. A prior-art sixteen phase-point, rectilinear, APSK (16-R-APSK) constellation 10 is shown in FIG. 1. Constellation 10 and other R-APSK modulations are conventionally referred to as quadrature amplitude modulation (QAM), but will be referred to herein using the generic term "R-APSK" to distinguish them from
10 polar APSK (P-APSK) modulations, discussed below.

R-APSK constellations represent a special class of constellations where one set of symbols is conveyed independently of another set of symbols. In 16-R-APSK (i.e. 16-QAM), two symbols are communicated using I phase constellation axis perturbations and two symbols are communicated using Q phase constellation axis perturbations.
15 Since the I and Q axes are orthogonal, the two sets of symbols have no influence over one another.

PTCM has been adapted to R-APSK constellations with moderate success. Typically, one primary modulation symbol (i.e., coded bit) and one secondary modulation symbol (i.e., uncoded bit) are conveyed by perturbations about each of the I
20 and Q axes. Unfortunately, conventional R-APSK constellations do not achieve rotationally invariant communication systems without accepting a tremendous degradation in performance (e.g. 4 dB). Without rotational invariance, the duration required for a decoder to achieve synchronization is much longer than with rotational invariance. When rotational invariance is sacrificed, conventional R-APSK
25 constellations achieve acceptable performance, but performance is still not optimized.

While R-APSK constellations achieve bandwidth efficiency over PSK modulation, they do so at a severe cost in power efficiency. Consequently, R-APSK constellations are particularly undesirable when used on peak power limited channels, such as characterize satellite communications. As illustrated by FIG. 1 for a specific 16-
30 R-APSK constellation, phase points reside in three concentric phase-point rings 18. Peak transmitter power is required to transmit phase points on an outer phase-point ring

18'. In random data, only 1/4 of the data are transmitted at this peak power. Accordingly, the peak power capability that must be provided in the transmitter is used to transmit only 1/4 of the data, resulting in an inefficient use of the peak power capability. In general, R-APSK constellations require an excessive number of phase-point rings 18, and this excessive number of rings causes an inefficient use of transmitter power so that, on average, an undesirably low amount of power is transmitted per bit.

Moreover, transmitter amplifiers introduce AM-AM and AM-PM distortions in the signals they amplify. AM-AM distortions characterize non-linear amplitude variations in an amplifier output signal which occur as a function of input amplitude but are not explained by amplifier gain. AM-PM distortions characterize phase variations in an amplifier output signal which occur as a function of input amplitude. The use of an excessive number of phase-point rings 18 in R-APSK for a given number of phase points requires transmitter amplifiers to operate at an excessive number of input amplitude states and causes an excessive amount of AM-AM and AM-PM distortions.

In theory, P-APSK constellations should have superior characteristics to R-APSK constellations, particularly in peak power limited channels. P-APSK constellations can be arranged so that a greater percentage of random data is transmitted using the peak power to achieve transmitter amplifier utilization efficiency. In addition, AM-AM and AM-PM distortions can theoretically be reduced if fewer rings are used to implement a phase constellation when compared to a R-APSK constellation having an equivalent number of phase points.

Unfortunately, conventional P-APSK constellations are not adapted to PTCM communication systems. Accordingly, such constellations have been proposed in either uncoded or in fully coded applications. Uncoded applications apply no convolutional coding to the communicated information bits, and fully coded applications apply convolutional coding to all communicated information bits. Uncoded applications are highly undesirable because they demonstrate significantly degraded performance when compared with equivalent pragmatic or fully coded applications. Fully coded applications are undesirable because they require the use of different convolutional encoders and decoders for different modulation orders.

Likewise, conventional receiver decoders have been unable to adequately adapt to a wide range of modulation types, orders and coding rates, particularly when configured to decode PTCM. For high speed digital communication applications, high data rates dictate that hardware rather than software, be primarily used to encode and decode data.

- 5 Conventional practices require new hardware to accommodate new convolutional codes, coding rates and phase-point constellations. This is an undesirably expensive and time consuming undertaking.

- 10 The puncturing of convolutional codes is a conventional technique for increasing a code rate at the expense of code strength. Prior art communication systems have applied puncturing to R-APSK and PSK, PTCM schemes. Punctured codes simply refrain from transmitting a portion of the convolutionally encoded bits between a transmitter and a receiver. Sufficient redundancy is built into the convolutional code that the original uncoded data stream may be reconstructed without communicating the omitted encoded bits. Even though certain encoded bits are not transmitted, they must be compensated for at the receiver. Accordingly erasures are inserted at the receiver for the omitted encoded bits prior to convolutional decoding.

- 15 The prior art systems which employ puncturing conventionally insert a constant erasure value that does not vary regardless of any particular received phase state. This technique works acceptably well when the conveyed encoded symbols are independent of one another. However, a cost of independently conveyed encoded symbols is the use inefficient phase constellation configurations for PTCM systems, such as R-APSK.

DISCLOSURE OF INVENTION

- 25 Accordingly, it is an advantage of the present invention that an improved pragmatic trellis-coded modulation (PTCM) demodulator and method for a data communication system are provided.

Another advantage of the present invention is that an improved PCTM demodulator and method therefor are provided that rely upon dependent encoded symbols.

Another advantage of the present invention is that an improved PCTM demodulator is provided that permits puncturing even though encoded symbols are dependent upon one another.

Another advantage of the present invention is that an improved PCTM demodulator is provided that is programmable to operate in connection with a variety of diverse modulation formats, orders and code rates.

The above and other advantages of the present invention are carried out in one form by a PCTM demodulator for decoding a punctured, convolutionally encoded data stream. The PCTM demodulator includes a phase estimator configured to generate phase estimate values, a depuncture circuit coupled to the phase estimator, the depuncture circuit being configured to periodically generate erasure values so that the erasure values vary in response to the phase estimate values, and a convolutional decoding circuit coupled to the depuncture circuit and configured to be responsive to the erasure values.

15

BRIEF DESCRIPTION OF DRAWINGS

A more complete understanding of the present invention may be derived by referring to the detailed description and claims when considered in connection with the Figures, wherein like reference numbers refer to similar items throughout the Figures, and:

20

FIG. 1 shows a sixteen phase-point, rectilinear, amplitude phase shift keyed (16-R-APSK) constellation used in a prior art data communication system;

FIG. 2 shows a block diagram of a pragmatic trellis-coded modulation (PTCM) data communication system configured in accordance with the teaching of the present invention;

25

FIG. 3 shows a block diagram of a PTCM modulator, as used in the communication system shown in FIG. 2;

FIG. 4 shows a sixteen phase-point, polar, amplitude phase shift keyed constellation produced by a first embodiment of a mapping circuit portion of the modulator shown in FIG. 3;

30

FIG. 5 shows a sixty-four phase-point, polar, amplitude phase shift keyed constellation produced by a second embodiment of the mapping circuit portion of the modulator shown in FIG. 3;

FIG. 6 shows a block diagram of a PCTM demodulator, as used in the
5 communication system shown in FIG. 2; and

FIG. 7 shows a flow chart of an exemplary puncture branch metrics process that can be used to generate branch metrics for a depuncture circuit of the PCTM demodulator of FIG. 6.

10 **BEST MODE FOR CARRYING OUT THE INVENTION**

FIG. 2 shows a block diagram of a digital communication system 20 configured in accordance with the teaching of the present invention. System 20 receives input data 22 to be encoded, modulated transmitted, received, demodulated, and decoded .

In an embodiment of the present invention utilizing concatenated coding, input
15 data 22 is passed into an input of a Reed-Solomon or other block encoder 24. An output of Reed-Solomon encoder 24 couples to an input of an interleaver 26. An output of interleaver 26 is coupled to an input of a pragmatic trellis-coded modulation (PTCM) modulator 28.

In an alternative embodiment of the present invention not utilizing concatenated
20 coding, Reed-Solomon encoder 24 and interleaver 26 are omitted and input data 22 is passed directly into the input of PTCM modulator 28.

For convenience, the input data supplied to and processed by PTCM modulator 28 are referred to herein as information bits 30, regardless of whether concatenated coding is implemented. The operation of PTCM modulator 28 is discussed in more detail
25 hereinbelow in connection with FIGs. 3 through 5.

An output of PTCM modulator 28 passes a quadrature transmission signal 31, in the form of phase-point data (discussed hereinbelow) to an input of a transmitter 32. Transmitter 32 transmits quadrature transmission signal 31, via a transmission antenna 34, as a digital communications signal 36 broadcast over a communication channel.

30 As illustrated in FIG. 2, digital communication signal 36 is invariably mixed with and corrupted to some degree by noise 37 within the communication channel. A

resultant corrupted digital communication signal 36' is received, via a reception antenna 38, by a receiver 40. In the preferred embodiments, receiver 40 implements a carrier-coherent reception scheme.

Receiver 40 produces a quadrature reception signal 41 having rectilinear (i.e. I and Q) or polar (i.e. ϕ and M, not shown) components. Quadrature reception signal 41 is then passed from an output of receiver 40 to an input of a pragmatic trellis-coded modulation (PTCM) demodulator 42. Demodulator 42, the counterpart of PTCM modulator 28, generates information-bit estimates 43, which are estimates of information bits 30. The operation of PTCM demodulator 42 is discussed in more detail hereinbelow in connection with FIGs. 6 and 7.

In the embodiment of the present invention utilizing concatenated encoding, an output of PTCM demodulator 42 passes information-bit estimates 43 to an input of a de-interleaver 44, the counterpart of interleaver 26. An output of de-interleaver 44 couples to an input of a Reed-Solomon or other block decoder 46, the counterpart of Reed-Solomon encoder 24. The output of Reed-Solomon decoder 46 is output data 45, and is the output of digital communication system 20. An output of Reed-Solomon decoder 46 indicating when output data 45 is valid, i.e., when corrupted digital communication signal 36' contains valid data, is fed back to PTCM demodulator 42 to aid in achieving node synchronization (i.e. to determine frame timing).

In the alternative embodiment of the present invention not utilizing concatenated encoding, de-interleaver 44 and Reed-Solomon decoder 46 are omitted, thus information-bit estimates 43 are output data 45 and the output of digital communication system 20. Since Reed-Solomon decoder 46 is omitted, other node synchronization techniques known to those skilled in the art may be used to identify frame timing.

FIG. 3 shows a block diagram of PTCM modulator 28, as used in digital communication system 20, in accordance with a preferred embodiment of the present invention. The following discussion refers to FIGs. 2 and 3.

A stream of information bits 30 is applied to an input of a parsing circuit 48. Parsing circuit 48 partitions information bits 30 between an output providing a primary information-bit stream 50 of uncoded information bits 51 and an output providing a

secondary information-bit stream 52 of to-be-coded information bits 53. Primary information-bit stream 50 may be distributed to an optional four-phase differential encoding circuit 54 and secondary information-bit stream 52 is distributed to a two-phase differential encoding circuit 56. Primary information-bit stream 50 is denoted as data (d) with a subscript of "2" or "3". Secondary information-bit stream 52 is denoted as data (d) with a subscript of "1". As discussed in more detail below, PTCM modulator 28 applies secondary modulation to secondary information-bit stream 52 and to primary information-bit stream 50.

In a preferred embodiment, discussed in greater detail below in conjunction with FIGs. 4 and 5, PTCM modulator 28 produces a fully-rotationally-invariant quadrature transmission signal 31. Optional differential encoders 54 and 56 are used in this fully-rotationally-invariant embodiment, but may be omitted if full rotational invariance is not desired. In this embodiment, uncoded information bits 51 of primary information-bit stream 50 are distributed to four-phase differential encoding circuit 54, and to-be-coded information bits 53 of secondary information-bit stream 52 are distributed to two-phase differential encoding circuit 56.

The present invention may be adapted to operate over a wide variety of modulation formats and orders and to produce a wide variety of effective code rates. However, for the sake of clarity the below-presented discussion focuses on a preferred embodiment which adapts the present invention to a 16-P-APSK modulation format and order to achieve various effective code rates. This 16-P-APSK preferred embodiment is further discussed in connection with a puncturing scheme that yields a 7/8 effective code rate. In other words, for every seven information bits 30 processed, eight symbols are transmitted. However, puncturing is not a requirement, and an effective code rate of 3/4 is easily achieved without puncturing.

In the preferred 16-P-APSK, rate 7/8 embodiment, parsing circuit 48 routes four of every seven information bits 30 into primary information-bit stream 50 as uncoded information bits 51 and three of every seven information bits 30 into secondary information-bit stream 52 as to-be-coded information bits 53. In particular, every zeroth, third, and fourth information bits 30 are routed to secondary information-bit stream 52 while every first, second, fifth, and sixth information bits 30 are routed to primary

information-bit stream 50, as indicated by data (d) superscripts in FIG. 3. These seven information bits 30 are distributed by parsing circuit 48 over a two-unit-interval time period 47 equivalent to two unit intervals of time 49. A unit interval of time 49 is indicated between post-parse vertical dotted lines 58 in FIG. 3.

5 Unit interval of time 49 is required by digital communication system 20 (FIG. 2) to communicate a single phase point. In the exemplary 16-P-APSK embodiment, four symbols are communicated by a single phase point per unit interval of time 49. In a 64-P-APSK embodiment, which is discussed below, six symbols are communicated by a single phase point per unit interval of time 49. Unit interval of time 49 represents the
10 reciprocal of the baud rate. Over each unit interval of time 49, the relative phase of quadrature components of digital communication signal 36 (FIG. 2) transitions from one set of phase data (i.e. one phase point) to another.

In the fully-rotationally-invariant preferred embodiment, during every two unit intervals of time 49, four-phase differential encoding circuit 54 processes four uncoded
15 information bits 51 and produces four convolutionally-uncoded information bits 51' that remain uncoded except for the differential encoding applied through differential encoding circuit 54. In other words, differential encoding circuit 54 processes and produces two convolutionally-uncoded information bits 51' per unit interval of time 49. A single unit interval of time 49 is indicated between pre-puncture vertical dotted lines
20 58' in FIG. 3. Differential encoding circuit 54 generates an output which represents the difference between the two uncoded information bits 51 being processed during a current (second) unit interval of time (t_1) 49' and the two uncoded information bits 51 processed in a preceding (first) unit interval of time (t_0) 49". Convolutionally-uncoded information bits 51' produced by differential encoding circuit 54 are referred to as
25 symbols (s).

Also in the fully-rotationally-invariant preferred embodiment, two-phase differential encoding circuit 56 processes one to-be-coded information bit 53 and produces one to-be-convolutionally-coded information bit 53' that remains uncoded except for the optional differential encoding applied through differential encoding
30 circuit 56. To-be-convolutionally-coded information bit 53' represents the difference between the to-be-coded information bit 53 being processed during second unit interval

of time (t_1) 49' and the to-be-coded information bit 53 processed during first unit interval of time (t_0) 49".

An input of a convolutional encoding circuit 62 couples to an output of two-phase differential encoding circuit 56. Convolutional encoding circuit 62 implements a transparent, recursive, $K=7$, rate $1/2$ convolutional ("Viterbi") encoder, but encoders having other parameters may also be used. Convolutional encoding circuit 62 may implement either a systematic or non-systematic code. Since, in the preferred embodiment, convolutional encoding circuit 62 implements a rate $1/2$ code, two symbols (s) are produced for each to-be-coded information bit 53 received from parsing circuit 48 (or to-be-convolutionally-coded information bit 53' received from two-phase differential encoding circuit 56, if differential encoding circuit 56 is included). Over the above-discussed two unit intervals of time 49, six encoded information bits 69, i.e., symbols (s), are produced in response to the three information bits 30 processed. FIG. 3 denotes the two symbols produced for each information bit 30 processed by using the subscripts "0" and "1".

Since convolutional encoding circuit 62 implements a transparent code, a linear relationship exists between the two outputs of convolutional encoding circuit 62. In other words, if identical data streams except for one complemented information bit 30 are presented to convolutional encoding circuit 62, then convolutional encoding circuit 62 will produce corresponding symbol pairs for primary and secondary information-bit streams 50 and 52 in which either both symbols are inverted or neither symbol is inverted.

Optionally, when puncturing is employed, the outputs of convolutional encoding circuit 62 provide unpunctured-encoded information bits 63 as a secondary data stream to a puncture controller 64. Puncture controller 64 selectively removes predetermined unpunctured-encoded information bits 63 and appropriately restructures the secondary information-bit stream 52 by delaying certain other unpunctured-encoded information bits 63 as necessary, thus producing encoded information bits 69.

For the rate $7/8$ example, two of unpunctured-encoded information bits 63 are punctured out of the secondary information-bit stream 52 during every two-unit-interval time period 47. As illustrated in FIG. 3 between pre-map vertical dotted lines 58",

during first unit interval of time (t_0) 49", puncturing does not occur. The zeroth bit d_1^0 of to-be-coded information bits 53 is converted by convolutional encoding circuit 62 into symbols s_1^0 and s_0^0 of encoded information bits 69. Bits s_1^0 and s_0^0 of encoded information bits 69 are concurrently output to puncture controller 64 from convolutional encoding circuit 62 during first unit interval of time (t_0) 49" of a two-unit-interval time period 47.

Puncturing does occur during second unit interval of time (t_1) 49' of the two-unit-interval time period 47. As illustrated in FIG. 3 during first unit interval of time (t_0) 49", zeroth bit d_1^0 of to-be-coded information bits 53 is converted by convolutional encoding circuit 62 into bits s_0^3 and s_1^3 of unpunctured-encoded information bits 63, but bit s_1^3 is punctured out. Similarly, the fourth data bit d_1^4 is converted by convolutional encoding circuit 62 into bits s_1^3 and s_0^3 of unpunctured-encoded information bits 63, but bit s_0^3 is punctured out. Bit s_0^3 of unpunctured-encoded information bits 63 is delayed so that it is output concurrently with bit s_1^3 from puncture controller 64 during the second unit interval of the two-unit-interval time period 47. Of course, a FIFO or other rate equalizing device (not shown) may be used by convolutional encoding circuit 62 and/or puncture controller 64 to accommodate the diverse number of encoding operations which occur in different unit intervals of time 49.

Accordingly, the output of puncture controller 64 is encoded information bits 69, and for the rate 7/8 embodiment, three information bits 30 are processed through convolutional encoding circuit 62 and puncture controller 64 over a two-unit-interval time period 47 to produce four symbols, i.e., encoded information bits 69. In other embodiments, other code rates may be achieved by extending the puncturing frame over different numbers of unit intervals of time 49 to puncture different fractions of the total number of unpunctured-encoded information bits 63 generated by convolutional encoding circuit 62.

So that PTCM modulator 28 can operate over a range of diverse puncturing rates, a PTCM encoder controller 66 couples to puncture controller 64 to provide a data set which defines a particular puncturing scheme to implement. In one embodiment (not shown), puncture controller 64 includes two shift registers which are loaded in parallel with a data set pattern from PTCM encoder controller 66 and which are clocked at twice the unit interval rate so that the data set patterns circulates therein. Puncture controller

64 also includes a multiplexer coupled to the output of convolutional encoding circuit 62 and controlled by the two shift registers. The multiplexer drives a FIFO memory. The data set patterns indicate which unpunctured-encoded information bits 63 to puncture out. Non-punctured unpunctured-encoded information bits 63 are loaded into the FIFO memory in the sequence defined by the data set and pulled out synchronously with the occurrence of unit intervals. However, those skilled in the art can devise alternate implementation techniques for puncture controller 64.

Convolutionally-uncoded information bits 51' from four-phase differential encoding circuit 54 couple to primary-stream (uncoded) inputs of a polar, amplitude phase shift keyed (P-APSK) mapping circuit 68. Similarly, encoded information bits 69 from an output of puncture controller 64 couple to secondary-stream (encoded) inputs of mapping circuit 68. In particular, during second unit interval of time (t_1) 49', 2^{N-2} convolutionally-uncoded information bits 51', i.e., symbols s_3^2 and s_2^1 (FIG. 3), drive the uncoded inputs of mapping circuit 68 in parallel and two encoded information bits 69, i.e., symbols s_0^0 and s_1^0 (FIG. 3), drive the encoded inputs of mapping circuit 68. The modulation order N equals four for the 16-P-APSK preferred embodiment depicted in FIG. 3 and equals six for the 64-P-APSK preferred embodiment discussed hereinbelow. Accordingly, mapping circuit 68 maps four or more symbols per unit interval of time 49.

P-APSK mapping circuit 68 implements a P-APSK phase-point constellation arranged as discussed hereinbelow. Mapping circuit 68 is desirably implemented as a random access memory (RAM) in which uncoded and encoded inputs represent memory address inputs. Thus, each mapping operation is performed by table look-up. In addition, data inputs of mapping circuit 68 couple to PTCM encoder controller 66 so that different phase-point constellations can be loaded into mapping circuit 68 to efficiently implement different modulation orders and coding rates.

P-APSK mapping circuit 68 is configured to concurrently map uncoded information bits 51 with encoded information bits 69. One mapping occurs for each unit interval of time 49. Each mapping causes a phase point to be produced. Each phase point is characterized by quadrature components which exhibit a predetermined relative magnitude and phase. During a given unit interval of time 49, a phase point is processed through transmitter 32 (FIG. 2) and conveyed to receiver 40 (FIG. 2) within digital

communication signal 36 (FIG. 2) over a communication channel. However, transmitter distortions, receiver distortions, noise 37 (FIG.2) within the communication channel, and other factors invariably corrupt signal 36 (i.e., produce corrupted digital communication signal 36'). This corruption causes receiver 40 to receive a somewhat
5 different phase point than was transmitted. Accordingly, the arrangement of phase points in a phase-point constellation has a significant influence on the ability of receiver 40 to successfully recover communicated data.

FIGs. 4 and 5 graphically illustrate P-APSK phase-point constellations 70 and 70' implemented by preferred embodiments of the present invention. Constellations 70 and
10 70' include phase points 72 arranged in an even number of concentric phase-point rings 74 in this fully-rotationally-invariant embodiment. A single phase-point ring 74 includes the set of phase points 72 which have substantially equal magnitude.

FIG. 4 shows a sixteen phase-point, polar, phase-shift keyed, fully-rotationally-invariant (16-P-APSK-FRI) constellation 70 produced by a first embodiment of P-
15 APSK mapping circuit 68 (FIG. 3) in accordance with a preferred embodiment of the present invention. The following discussion refers to FIG. 4.

16-P-APSK-FRI constellation 70 is derived from a 4-QPSK constellation (not shown) which is not well-suited to pragmatic encoding but which demonstrates desirable theoretical performance characteristics for uncoded or fully coded
20 communications. The 4-QPSK constellation has a single phase-point ring of four phase points arranged at 90° intervals, implements a modulation order of two, and is used to communicate two symbols per unit interval.

16-P-APSK-FRI constellation 70 is derived from the original 4-QPSK constellation described above by providing four phase points 72 for each phase point in
25 the original constellation. To do so, the single phase-point ring of the original constellation is expanded into an outer (only) ring pair 75 having like numbers of phase points 72 per ring 74.

For outer ring pair 75, the original phase-point ring becomes an outer outer-pair ring 75'. Outer outer-pair ring 75' is populated by providing two phase points 72 for each
30 of the four original phase points to achieve a total of eight phase points 72. An inner outer-pair ring 75" is then added. Inner outer-pair ring 75" is populated by providing one

phase point 72 on inner outer-pair ring 75" for each phase point 72 on outer outer-pair ring 75' to achieve a second total of eight phase points 72. All eight phase points 72 on each of outer and inner outer-pair rings 75' and 75" are uniformly distributed in phase, with phase points 72 on inner outer-pair ring 75" symmetrically interleaved with and
5 substantially bisecting the phase angles of phase points 72 on outer outer-pair ring 75'. Phase points 72 of outer and inner outer-pair rings 75' and 75" are therefore at 45° intervals, with phase points 72 of inner outer-pair ring 75" rotated 22.5° with respect to phase points 72 of outer outer-pair ring 75'.

FIG. 5 shows a sixty-four phase-point, polar, amplitude phase-shift keyed, fully-
10 rotationally-invariant (64-P-APSK-FRI) constellation 70' produced by a second embodiment of P-APSK mapping circuit 68 (FIG. 3) in accordance with the teaching of the present invention. The following discussion refers to FIG. 5.

64-P-APSK-FRI constellation 70' is derived from a 12/4, 16-P-APSK constellation (not shown) which is not well-suited to pragmatic encoding but which
15 demonstrates desirable theoretical performance characteristics for uncoded or fully coded communications. The 12/4, 16-P-APSK constellation has an outer phase-point ring 74 of twelve phase points arranged at 30° intervals, an inner phase-point ring 74 of four phase points arranged at 90° intervals, implements a modulation order of four, and is used to communicate four symbols per unit interval.

20 64-P-APSK-FRI constellation 70' is derived from the original 12/4, 16-P-APSK constellation described above by providing four phase points 72 for each phase point in the original constellation. To do so, the two phase-point rings 74 of the original constellation are expanded into an outer ring pair 75 and an inner ring pair 76, each of which has like numbers of phase points 72 per ring 74.

25 For outer ring pair 75, the original outer phase-point ring becomes an outer outer-pair ring 75'. Outer outer-pair ring 75' is populated by providing two phase points 72 for each of the twelve original outer-ring phase points to achieve a total of twenty-four phase points 72. An inner outer-pair ring 75" is then added. Inner outer-pair ring 75" is populated by providing one phase point 72 on inner outer-pair ring 75" for each phase
30 point 72 on outer outer-pair ring 75' to achieve a second total of twenty-four phase points 72. All twenty-four phase points 72 on each of outer and inner outer-pair rings 75'

and 75" are uniformly distributed in phase, with phase points 72 on inner outer-pair ring 75" symmetrically interleaved with and substantially bisecting the phase angles of phase points 72 on outer outer-pair ring 75'. Phase points 72 of outer and inner outer-pair rings 75' and 75" are therefore at 15° intervals, with phase points 72 of inner outer-pair ring 75" rotated 7.5° with respect to phase points 72 of outer outer-pair ring 75'.

For inner ring pair 76, the original inner phase-point ring becomes an outer inner-pair ring 76'. Outer inner-pair ring 76' is populated by providing two phase points 72 for each of the four original inner-ring phase points to achieve a total of eight phase points 72. An inner inner-pair ring 76" is then added. Inner inner-pair ring 76" is populated by providing one phase point 72 on inner inner-pair ring 76" for each phase point 72 on outer inner-pair ring 76' to achieve a second total of eight phase points 72. All eight phase points 72 on each of outer and inner inner-pair rings 76' and 76" are uniformly distributed in phase, with phase points 72 on inner inner-pair ring 76" symmetrically interleaved with and substantially bisecting the phase angles of phase points 72 on outer inner-pair ring 76'. Phase points 72 of outer and inner inner-pair rings 76' and 76" are therefore at 45° intervals, with phase points 72 of inner inner-pair ring 76" rotated 22.5° with respect to phase points 72 of outer inner-pair ring 76'.

Referring to FIGs. 4 and 5, preferred labeling schemes are applied to phase points 72. The labeling schemes define primary and secondary sub-constellations. For 16-P-APSK-FRI constellation 70 and 64-P-APSK-FRI constellation 70', the labeling schemes cooperate in achieving rotational invariance, which is discussed hereinbelow.

The preferred labeling schemes are a set of binary codes in which a unique binary code is associated with each phase point 72. By applying the indicated binary code to inputs of P-APSK mapping circuit 68 (FIG. 3), the indicated phase point 72 is produced. Likewise, when receiver 40 (FIG. 2) receives a phase point 72 proximate those phase points 72 indicated in FIGs. 4 and 5, PCTM demodulator 42 (FIG. 2) desirably generates data estimates corresponding to the indicated binary codes.

The preferred labeling schemes denote two bits to the right of a radix point and 2^{N-2} bits to the left of the radix point for each binary code, where N equals the modulation order. The modulation order is four for 16-P-APSK-FRI constellation 70 and six for 64-P-APSK-FRI constellation 70'. The bits to the right of the radix point

indicate encoded information bits 69, i.e., information bits 30 in secondary information-bit stream 52, and the bits to the left of the radix point indicate uncoded information bits 51, i.e., information bits 30 in primary information-bit stream 50. However, the radix point has no significance other than distinguishing encoded information bits 69 from
5 uncoded information bits 51. Nothing requires encoded information bits 69 and uncoded information bits 51 to be in any particular order relative to each other. Rather, all encoded information bits 69 and uncoded information bits 51 are independent of each other. While encoded information bits 69 and uncoded information bits 51 for constellations 70 and 70' are independent of each other, the resulting phase-point
10 symbols into which the information bits 30 are mapped by P-APSK mapping circuit 68 are not independent from one another in order to achieve desirable performance characteristics.

FIG. 6 shows a block diagram of a portion of receiver 40 and of PCTM demodulator 42. Referring to FIG. 6, an intermediate-frequency (IF) signal is supplied at
15 a node 88 within receiver 40. Node 88 couples to a mixing circuit 90, where the IF signal is downconverted to baseband. A phase estimator 92 couples to mixing circuit 90 to convert the baseband signal into quadrature data. Phase estimator 92 may include analog-to-digital conversion and may output the quadrature data in accordance with either a polar (ϕ , M) or rectilinear (I,Q) coordinate system. FIG. 6 denotes the polar
20 coordinate system for convenience, but those skilled in the art will appreciate that all operations discussed herein in connection with the polar coordinate system may likewise be carried out in accordance with a rectilinear coordinate system.

The magnitude portion of the quadrature data is supplied to a magnitude processor 94, and the phase portion of the quadrature data is supplied to a positive input of a
25 summing circuit 96. Magnitude processor 94 outputs a phase angle offset ($\Delta\phi$) that is determined as a function of magnitude ($f(M)$). Referring to FIG. 4, magnitude processor 94 desirably outputs a phase angle offset of approximately 22.5° for magnitude values approximately equivalent to the magnitude of inner outer-pair ring 75" and a phase angle offset of approximately 0° for magnitude values approximately equivalent to the
30 magnitude of outer outer-pair ring 75'. A wide range of functions that provide these

phase angle offsets for the indicated magnitude values can be implemented by magnitude processor 94. The phase angle offset from magnitude processor 94 is supplied to a negative input of summing circuit 96.

Summing circuit 96 provides a phase angle that has been adjusted in response to the magnitude of quadrature data. While the quadrature data from phase estimator 92 may be noisy, the adjusted phase angle will tend to exhibit values that are concentrated at the phase values indicated in the outer outer-pair ring 75" of 16-P-APSK-FRI constellation 70. In other words, summing circuit 96 provides adjusted phase angle data with eight locally discrete average values for constellation 70, and those eight values are integral multiples of 45° .

The output from summing circuit 96 couples to a modulo processor 98. Modulo processor 98 is configured to output deviations from the discrete phase values about which the adjusted phase angle data varies. These deviations are converted into an analog signal through a digital-to-analog (D/A) converter 100, then filtered in a loop filter 102. Loop filter 102 drives a carrier tracking loop oscillator 104, and an output of oscillator 104 couples back to mixing circuit 90.

Accordingly, magnitude processor 94, summing circuit 96, modulo processor 98, D/A converter 100, loop filter 102, and carrier tracking loop oscillator 104 together form a carrier tracking loop 106. Carrier tracking loop 106 allows receiver 40 to recover the phase of digital communication signal 36 (FIG. 2) so that receiver 40 can coherently detect signal 36. Due to adjusted phase angle data provided by summing circuit 96, carrier tracking loop 106 locks at phase values that are integral multiples of 45° for 16-P-APSK-FRI constellation 70 depicted in FIG. 4.

In a preferred embodiment, a PTCM decoder controller 107 couples to modulo processor 98 and optionally to magnitude processor 94 (coupling not shown). PTCM decoder controller 107 provides data sets which program carrier tracking loop 106 to operate upon diverse phase-point constellations. For example, magnitude and modulo processor functions different from those used to accommodate 16-P-APSK-FRI constellation 70 (FIG. 4) may be programmed into magnitude processor 94 and modulo processor 98 to accommodate 64-P-APSK-FRI constellation 70' (FIG. 5) or 64-P-APSK-NFRI constellation 70".

The quadrature data from phase estimator 92 are also routed to a delay element 108, inputs of a no-erasure branch metrics processor 110, and inputs of a depuncture circuit 112. Depuncture circuit 112 includes an erasure branch metrics processor 114 and a de-puncture controller 116. The quadrature data from phase estimator 92 are
5 routed to inputs of erasure branch metrics processor 114.

No-erasure branch metrics processor 110 is a conventional branch metrics processor but is specifically adapted to accommodate the phase-point constellation being received (e.g. constellation 70 and 70'). Those skilled in the art are familiar with branch metric processors and with various techniques for generating branch metrics.
10 Desirably, no-erasure branch metrics processor 110 is implemented using a random access memory (RAM), with quadrature data from phase estimator 92 being applied to address inputs of the RAM. Desirably, a data input to no-erasure branch metrics processor 110 couples to PTCM decoder controller 107 so that different branch metrics are programmed into no-erasure branch metrics processor 110 to accommodate different
15 modulation schemes.

As discussed above, two encoded information bits 69 and two uncoded information bits 51 are conveyed during each unit interval of time 49 as four symbols. Accordingly, for each unit interval the quadrature data from phase estimator 92 describes two encoded/secondary symbols and two uncoded/primary symbols. These
20 encoded symbols were denoted above in connection with FIG. 3 as s_x^1 and s_x^0 . For each unit interval, no-erasure branch metrics processor 110 outputs four soft decision values corresponding to the inverse log likelihoods of the two encoded symbols having four different data values. Output L_{00} provides a value describing the likelihood of s_0 being a "0" and s_1 being a "0", output L_{01} provides a value describing the likelihood of s_0 being
25 a "0" and s_1 being a "1", output L_{10} provides a value describing the likelihood of s_0 being a "1" and s_1 being a "0", and output L_{11} provides a value describing the likelihood of s_0 being a "1" and s_1 being a "1". Outputs L_{00} through L_{11} from no-erasure branch metrics processor 110 are routed through a multiplexer (MUX) 118 to four
30 corresponding inputs of a convolutional decoding circuit 120. In particular, these outputs are so routed during unit intervals where puncturing does not occur. The one of every two unit intervals in which symbols s_1^0 and s_0^0 are communicated represents a unit

interval for which puncturing does not occur in the rate 7/8 example discussed above in connection with FIG. 3.

Erasure branch metrics processor 114 outputs different branch metrics from those provided by no-erasure branch metrics processor 110. In particular, the likelihood values
5 generated by erasure branch metrics processor 114 are compensated to null out the influence of a second symbol during unit intervals when puncturing has occurred. The one of every two unit intervals in which symbols s_1^3 and s_0^3 are communicated represents a unit interval for which puncturing does occur in the rate 7/8 example discussed above in connection with FIG. 3.

10 Erasure branch metrics processor 114 has four outputs. A L_{0x} output provides a value describing the likelihood of s_0 being a "0" regardless of whether s_1 was a "0" or a "1". This output is duplicated and routed through multiplexer 118 to L_{00} and L_{01} inputs of convolutional decoding circuit 120. A L_{1x} output provides a value describing the likelihood of s_0 being a "1" regardless of whether s_1 was a "0" or a "1". This output is
15 duplicated and routed through multiplexer 118 to L_{10} and L_{11} inputs of convolutional decoding circuit 120. A L_{x0} output provides a value describing the likelihood of s_1 being a "0" regardless of whether s_0 was a "0" or a "1". This output is duplicated and routed through multiplexer 118 to L_{00} and L_{10} inputs of convolutional decoding circuit 120. A L_{x1} output provides a value describing the likelihood of s_1 being a "1" regardless of
20 whether s_0 was a "0" or a "1". This output is duplicated and routed through multiplexer 118 to L_{01} and L_{11} inputs of convolutional decoding circuit 120.

During unit intervals when puncturing does occur, the L_{0x} and L_{1x} outputs and their duplicates are routed through multiplexer 118 and the L_{x0} and L_{x1} outputs and their duplicates are routed through multiplexer 118. The L_{0x} and L_{1x} outputs and their
25 duplicates provide symbol branch metrics and erasure value branch metrics for the conveyed symbol s_0^3 and its punctured pair mate s_1^3 (FIG. 3). Likewise, the L_{x0} and L_{x1} outputs and their duplicates provide symbol branch metrics and erasure value branch metrics for the conveyed symbol s_1^3 and its punctured pair mate s_0^3 (FIG. 3).

Erasure branch metrics processor 114 is desirably implemented using RAM, with
30 quadrature phase estimate data driving the RAM address inputs. Desirably, a data input of the RAM couples to PTCM decoder controller 107 so that new erasure branch

metrics may be programmed into the RAM for different types of modulations. Likewise, de-puncture controller 116 desirably couples to PTCM decoder controller 107 and is programmed with data sets that define timing for operating multiplexer 118 so that the outputs from branch metrics processors 110 and 114 are appropriately routed through multiplexer 118. In one embodiment (not shown), de-puncture controller 116 includes two shift registers loaded in parallel with a data set pattern from PTCM decoder controller 107 and clocked at twice the unit interval rate so that the data set patterns circulate therein. These data set patterns drive selection inputs of multiplexer 118.

FIG. 7 shows a flow chart of an exemplary puncture branch metrics process 122 that can be used to generate branch metrics for depuncture circuit 112. Desirably, process 122 is performed off-line so that branch metrics are calculated in advance and then programmed into depuncture circuit 112 prior to their use. Process 122 is an exemplary process that illustrates the manner in which erasure values and erasure value likelihoods preferably vary in response to phase estimate values.

Puncture branch metrics process 122 operates in a loop wherein one iteration of the loop is performed for each possible phase estimate value (ϕ, M) that can be generated by phase estimator 92 (FIG. 6). A derivation task 124 of process 122 is performed to derive the next phase estimate value (ϕ, M) to be processed. After task 124, a series of calculation tasks are performed.

A calculation task 126 determines the L_{0x} output for the current phase estimate value (ϕ, M) . Task 126 calculates chances or probabilities "A" and "B". Chance or probability A represents the likelihood that s_0^3 is a "0" assuming a priori knowledge that its post-puncturing mate s_1^3 is a "1" and given the current phase estimate value (ϕ, M) . Chance or probability B represents the likelihood that s_0^3 is a "0" assuming a priori knowledge that its post-puncturing mate s_1^3 is a "0" and given the current phase estimate value (ϕ, M) . In addition, task 126 finds the average of chances A and B and uses that average for the likelihood value L_{0x} at the current phase estimate value (ϕ, M) . As discussed above, the encoded symbols are not independent of one another through the use of constellations such as 16-P-APSK-FRI constellation 70 (FIG. 4) and 64-P-APSK-

FRI constellation 70' (FIG. 5). But, the influence that symbol s_1^3 exerts on symbol s_0^3 is nulled out.

Calculation tasks 128, 130, and 132 calculate chances "A" and "B" and the resulting average in a similar manner. Task 128 determines the L_{1x} output for the current
 5 phase estimate value (ϕ, M) . Chance or probability A now represents the likelihood that s_0^3 is a "1" assuming a priori knowledge that its post-puncturing mate s_1^3 is a "1" and given the current phase estimate value (ϕ, M) . Chance or probability B now represents the likelihood that s_0^3 is a "1" assuming a priori knowledge that its post-puncturing mate s_1^3 is a "0" and given the current phase estimate value (ϕ, M) . The average of chances A
 10 and B is used for the likelihood value L_{1x} at the current phase estimate value (ϕ, M) .

Calculation task 130 determines the L_{x0} output for the current phase estimate value (ϕ, M) . Chance or probability A now represents the likelihood that s_1^3 is a "0" assuming a priori knowledge that its post-puncturing mate s_0^3 is a "1" and given the current phase estimate value (ϕ, M) . Chance or probability B now represents the
 15 likelihood that s_1^3 is a "0" assuming a priori knowledge that its post-puncturing mate s_0^3 is a "0" and given the current phase estimate value (ϕ, M) . The average of chances A and B is used for the likelihood value L_{x0} at the current phase estimate value (ϕ, M) .

Calculation task 132 determines the L_{x1} output for the current phase estimate value (ϕ, M) . Chance or probability A now represents the likelihood that s_1^3 is a "1" assuming a priori knowledge that its post-puncturing mate s_0^3 is a "1" and given the
 20 current phase estimate value (ϕ, M) . Chance or probability B now represents the likelihood that s_1^3 is a "1" assuming a priori knowledge that its post-puncturing mate s_0^3 is a "0" and given the current phase estimate value (ϕ, M) . The average of chances A and B is used for the likelihood value L_{x1} at the current phase estimate value (ϕ, M) .

25 After calculation task 132, a query task 134 determines whether all possible phase estimate values (ϕ, M) have been processed. If less than all possible phase estimate values (ϕ, M) have been processed, program control loops back to derivation task 124 to process another phase estimate value. When all possible phase estimate values (ϕ, M) have been processed, program control stops. Branch metric data for storing in erasure
 30 branch metrics processor 114 has been generated.

Referring back to FIG. 6, convolutional decoding circuit 120 performs a complementary operation to that performed by convolutional encoding circuit 62 (FIG. 3). Accordingly, convolutional decoding circuit 120 produces one information-bit estimate 43 for each set of four likelihood values it receives from multiplexer 118. In the
5 exemplary rate 7/8 embodiment, convolutional decoding circuit 120 produces three information-bit estimates 43 for every two unit intervals. Those skilled in the art will appreciate that convolutional decoding circuit 120 may process each set of likelihood values from multiplexer 118 over numerous unit intervals (e.g. typically more than sixty-four) before generating a data estimate. In addition, those skilled in the art will
10 appreciate that a FIFO or other rate converting device (not shown) may be used for buffering between multiplexer 118 and convolutional decoding circuit 120.

An output of convolutional decoding circuit 120 provides a secondary stream of information-bit estimates to a rate 1/2, convolutional encoding circuit 136 and to a two-phase differential decoding circuit 138. Differential decoding circuit 138 complements
15 the operation of two-phase differential encoding circuit 56 of PTCM modulator 28 (FIG. 3). Due to a possible phase synchronization ambiguity, receiver 40 may synchronize at a phase state that causes the outputs from convolutional decoding circuit 120 to be inverted from their true states. Differential decoding circuit 138 recovers the true data regardless of whether the data estimates from convolutional decoding circuit 120 are
20 inverted.

Convolutional encoding circuit 136 is desirably identical to convolutional encoding circuit 62 of PTCM modulator 28 (FIG. 3). If convolutional encoding circuit 62 implements a given rate $1/N$ code, with $N > 1$, then convolutional encoding circuit 136 implements that same code. Accordingly, if the secondary stream of information-bit
25 estimates correctly estimates secondary information-bit stream 52 (FIG. 3), then a secondary stream of symbol estimates produced by convolutional encoding circuit 136 includes symbol estimates that equal corresponding symbols produced by convolutional encoding circuit 62 in PTCM modulator 28. Three pairs of symbol estimates are produced by convolutional encoding circuit 136 for every two unit intervals in the rate
30 7/8 example discussed herein. Since convolutional encoding circuit 136 desirably implements a transparent code, if it receives inverted data due to the possible phase

ambiguity, then both output symbols are inverted. Convolutional encoding circuit 136 generates a re-encoded bit stream which is provided to a puncture controller 140.

Puncture controller 140 provides substantially the same operation as is provided by puncture controller 64 in PTCM modulator 28 (FIG. 3). Accordingly, puncture
5 controller 140 generates a symbol stream identical to that used to drive P-APSK mapping circuit 68 in PTCM modulator 28 (FIG. 3), assuming that no bit errors have occurred. Puncture controller 140 couples to de-puncture controller 116 to obtain timing synchronization to identify when to puncture out re-coded symbols and when to combine unpunctured symbols generated from different data estimates. Likewise,
10 puncture controller 140 desirably couples to PTCM decoder controller 107 so that it is programmed with a data set that defines the puncture timing.

Outputs from delay element 108 and from puncture controller 140 couple to a slicer, implemented in the preferred embodiment as a demodulation look-up table 142. Delay element 108 delays estimated phase values by a sufficient duration to achieve
15 coincidence between symbols of the primary and secondary streams. Coincidence is achieved when a re-encoded bit stream symbol estimate from puncture controller 140 is output at the same instant the phase estimate value which conveyed the re-encoded bit stream symbol estimate is output from delay element 108.

Demodulation look-up table 142 performs two operations in the preferred
20 embodiment. In a first operation, secondary modulation, as specified by the secondary re-encoded bit stream, is removed from the phase estimate value presented for each unit interval. Referring to FIG. 4, the secondary modulation for 16-P-APSK-FRI constellation 70 is removed by rotating the phase estimate value by 45° when the least significant re-encoded bit equals a one and rotating the phase estimate value by 0° when
25 the least significant re-encoded bit equals a zero. In addition to this selective rotation, an additional rotation of 22.5° is performed when the two re-encoded bits do not equal each other, but no additional rotation is performed when the two re-encoded bits equal each other. After removing the secondary modulation, the phase estimates describe the QPSK primary modulation from which constellation 70 was derived.

30 After removal of the secondary modulation, demodulation look-up table 142 performs the second of its two operations. In this second operation a conventional

QPSK slicing or demodulation operation is performed to estimate which two primary/uncoded information bits are conveyed by the primary QPSK modulation. The resulting data estimates are output from demodulation look-up table 142 at a rate of two primary/uncoded data bit estimates per unit interval.

- 5 In the preferred embodiment, the above-described two operations of demodulation look-up table 142 are simultaneously performed through a table look-up operation. In this preferred embodiment, demodulation look-up table 142 is implemented in RAM. A data input of the RAM couples to PTCM decoder controller 107 so that a data set which both removes the secondary modulation and demodulates a given phase-point
- 10 constellation is programmed into the RAM as required. Accordingly, for any combination of data estimate input and re-encoded bit stream, an output is provided indicating the resulting uncoded information bit estimates, often referred to as hard decisions. Moreover, those skilled in the art will appreciate that various data compression techniques may be applied to minimize the size of the RAM. By
- 15 implementing demodulation look-up table 142 in the form of a demodulation look-up table that simultaneously compensates for or otherwise removes secondary modulation from phase estimates, a variety of modulation types can be demodulated using one set of hardware. Thus, the same slicer that removes secondary modulation and performs a QPSK slicing operation to process 16-P-APSK-FRI constellation 70 (FIG. 4) can be re-
- 20 programmed to remove secondary modulation and perform a 12/4, P-APSK slicing operation to process 64-P-APSK-FRI constellation 70' (FIG. 5) and to process other phase-point constellations.

- The uncoded/primary bit estimates output from demodulation look-up table 142 are input to a four-phase differential decoding circuit 144. Differential decoding circuit
- 25 144 complements the operation of four-phase differential encoding circuit 54 of PTCM modulator 28 (FIG. 3) in support of rotational invariant operation. As discussed above, due to a possible phase ambiguity, receiver 40 may synchronize at an ambiguous phase state. However, the absolute phase reference currently being used by receiver 40, has no influence over the changes in phase estimate values from unit interval to unit interval.
- 30 Accordingly, differential decoding circuit 144 recovers the true data regardless of the phase state to which receiver 40 has synchronized. The outputs of differential decoding

circuits 138 and 144, hence the output of PCTM demodulator 42, are information-bit estimates 43 (FIG. 2).

In summary, the present invention provides an improved data communication system and method. A P-APSK phase-point constellation is provided with a labeling
5 scheme that causes its primary and secondary sub-constellations to be suitable for PTCM communication schemes. In particular, the P-APSK phase constellation is desirably used in peak power limited channels. The present invention also accommodates puncturing even though encoded symbols are dependent upon one another. Moreover, the PTCM data communication system is programmable to operate
10 in connection with a variety of diverse modulation formats, orders and code rates.

The present invention has been described above with reference to preferred embodiments. However, those skilled in the art will recognize that changes and modifications may be made in these preferred embodiments without departing from the scope of the present invention. These and other changes and modifications which are
15 obvious to those skilled in the art are intended to be included within the scope of the present invention.

CLAIMS

What is claimed is:

1. A demodulator (42) for decoding a punctured, convolutionally encoded data stream, said demodulator (42) comprising:

a phase estimator (92) configured to generate phase estimate values;

a depuncture circuit (112) coupled to said phase estimator (92), said depuncture circuit (112) being configured to periodically generate erasure values so that said erasure values vary in response to said phase estimate values; and

a convolutional decoding circuit (120) coupled to said depuncture circuit (112) and configured to be responsive to said erasure values.

2. A demodulator (42) as claimed in claim 1 wherein:

said convolutionally encoded data stream is received throughout a multiplicity of unit intervals of time (49), puncturing does not occur in a first portion of said unit intervals of time (49), and puncturing does occur in a second portion of said unit intervals of time (49);

said demodulator (42) additionally comprises a first branch metric processor (110) configured to generate branch metrics for use by said convolutional decoding circuit (120) during said first portion of said unit intervals of time (49), said first branch metric processor (110) being responsive to said phase estimate values; and

said depuncture circuit (112) comprises a second branch metric processor (114) configured to generate branch metrics for use by said convolutional decoding circuit (120) during said second portion of said unit intervals of time (49), said second branch metric processor (114) being responsive to said phase estimate values.

3. A demodulator (42) as claimed in claim 2 wherein:

said first branch metric processor (110) supplies two unpunctured likelihood values to said convolutional decoding circuit (120) for each phase estimate value to which said first branch metric processor (110) responds; and

said second branch metric processor (114) is configured to provide a first likelihood value and a duplicate of said first likelihood value to said convolutional decoding circuit (120) for each phase estimate value to which said second branch metric processor (114) responds.

4. A demodulator (42) as claimed in claim 3 wherein said second branch metric processor (114) is configured to provide a second likelihood value and a duplicate of said second likelihood value to said convolutional decoding circuit (120) for each phase estimate value to which said second branch metric processor (114) responds.

5. A demodulator (42) as claimed in claim 4 wherein:

said second branch metric processor (114) is further configured to supply a third likelihood value and a duplicate of said third likelihood value to said convolutional decoding circuit (120) so that said first likelihood value and duplicate are routed to first and second inputs of said convolutional decoding circuit (120) for each phase estimate value to which said second branch metric processor (114) responds, and so that said third likelihood value and duplicate are routed to third and fourth inputs of said convolutional decoding circuit (120) for each phase estimate value to which said second branch metric processor (114) responds;

said second branch metric processor (114) is further configured to supply a fourth likelihood value and a duplicate of said fourth likelihood value to said convolutional decoding circuit (120) so that said second likelihood value and duplicate are routed to said first and third inputs of said convolutional decoding circuit (120) for each phase estimate value to which said second branch metric processor (114) responds, and so that said fourth likelihood value and duplicate are routed to said second and fourth inputs of said convolutional decoding circuit (120) for each phase estimate value to which said second branch metric processor (114) responds; and

said first branch metric processor (110) supplies fifth, sixth, seventh, and eighth likelihood values to said first, second, third, and fourth inputs of said convolutional decoding circuit (120) for each phase estimate value to which said first branch metric processor (110) responds.

6. A demodulator (42) as claimed in claim 2 wherein:
each phase estimate value conveys first and second convolutionally encoded symbols;
for one of said phase estimate values, said second branch metric processor (114) generates a value describing the likelihood that said first symbol exhibits a predetermined polarity; and
said second branch metric processor (114) is configured so that said second branch metric processor likelihood value is compensated to null out influence of said second symbol.
7. A demodulator (42) as claimed in claim 6 wherein:
said first branch metric processor (110) generates a value describing the likelihood that said first symbol exhibits said predetermined polarity; and
said first branch metric processor (110) is configured so that said first branch metric processor likelihood value is influenced by said second symbol.
8. A demodulator (42) as claimed in claim 6 wherein:
said likelihood value approximately equals an average of a first chance value and a second chance value;
said first chance value represents the likelihood that said first symbol exhibits said predetermined polarity given said one phase estimate value and assuming a priori knowledge that said second symbol exhibits said predetermined polarity; and
said second chance value represents the likelihood that said first symbol exhibits said predetermined polarity given said one phase estimate value and assuming a priori knowledge that said second symbol exhibits a polarity opposite to said predetermined polarity.
9. A demodulator (42) as claimed in claim 6 wherein:

for said one phase estimate value, said second branch metric processor (114) generates a value describing the likelihood that said second symbol exhibits said predetermined polarity; and

said second branch metric processor (114) is configured so that said second symbol likelihood value is compensated to null out influence of said first symbol.

10. A demodulator (42) as claimed in claim 9 wherein:

said first symbol likelihood value approximately equals an average of a first chance value and a second chance value;

said first chance value represents the likelihood that said first symbol exhibits said predetermined polarity given said one phase estimate value and assuming a priori knowledge that said second symbol exhibits said predetermined polarity;

said second chance value represents the likelihood that said first symbol exhibits said predetermined polarity given said one phase estimate value and assuming a priori knowledge that said second symbol exhibits a polarity opposite to said predetermined polarity;

said second symbol likelihood value approximately equals an average of a third chance value and a fourth chance value;

said third chance value represents the likelihood that said second symbol exhibits said predetermined polarity given said one phase estimate value and assuming a priori knowledge that said first symbol exhibits said predetermined polarity; and

said fourth chance value represents the likelihood that said second symbol exhibits said predetermined polarity given said one phase estimate value and assuming a priori knowledge that said first symbol exhibits a polarity opposite to said predetermined polarity.

11. A demodulator (42) as claimed in claim 1 wherein said depuncture circuit (112) comprises a memory element configured to be downloaded with different data sets, said different data sets being configured to control depuncturing for different code rates.

12. A demodulator (42) as claimed in claim 1 wherein:
said data stream is configured in accordance with a polar, amplitude phase shift keyed (P-APSK), pragmatic trellis-coded modulation (PTCM) scheme;
said convolutional decoding circuit (120) is configured to provide a second stream of data estimates;
said demodulator (42) additionally comprises a convolutional encoding circuit (136) adapted to encode said second stream of data estimates to produce a re-encoded bit stream; and
said demodulator (42) additionally comprises a slicer (142) configured to form a first stream of data estimates in response to said re-encoded bit stream and said phase estimate values.

13. A demodulator (42) as claimed in claim 1 wherein:
said data stream is configured in accordance with a polar, amplitude phase shift keyed (P-APSK) modulation scheme;
said phase estimate values convey quadrature phase and magnitude data; and
said demodulator (42) additionally comprises a carrier tracking loop (106) having an input coupled to said phase estimator (92) and being configured to adjust said quadrature phase data in response to said quadrature magnitude data to generate a phase-adjusted signal, said phase-adjusted signal being used for carrier tracking.

14. A demodulator (42) as claimed in claim 1 wherein:
said demodulator (42) is configured to produce estimates of information bits (30) modulated to implement phase points (72) in a phase-point constellation (70,70'), wherein said constellation (70,70') has 2^N of said phase points (72) implemented through the modulation of N of said information bits (30) per unit interval of time (49), where "N" is an integer number, 2^{N-2} of said 2^N information bits (30) being uncoded information bits (51) and two of said 2^N information bits (30) being encoded information bits (69).

15. A method for decoding a punctured, convolutionally encoded data stream comprising the steps of:

- a) generating phase estimates values from a received signal (36');
- b) periodically producing erasure values so that said erasure values vary in response to said phase estimate values; and
- c) convolutionally decoding in response to said erasure values.

16. A method as claimed in claim 15 wherein:

said convolutionally encoded data stream is received throughout a multiplicity of unit intervals of time (49), puncturing does not occur in a first portion of said unit intervals of time (49), and puncturing does occur in a second portion of said unit intervals of time (49);

said method additionally comprises the step of generating first branch metrics for use in said decoding step during unit intervals of time (49) where puncturing does not occur, said first branch metrics being responsive to said phase estimate values; and

said erasure value producing step comprises the step of generating second branch metrics for use in said decoding step during unit intervals of time (49) where puncturing does occur, said second branch metrics being responsive to said phase estimate values.

17. A method as claimed in claim 16 wherein:

said first branch metric generating step generates two likelihood values for each phase estimate value to which said first branch metric generating step responds; and

said second branch metric generating step generates a first likelihood value and a duplicate of said first likelihood value for each phase estimate value to which said second branch metric generating step responds.

18. A method as claimed in claim 17 wherein said second branch metric generating step comprises the step of providing a second likelihood value and a duplicate of said second likelihood value for each phase estimate value to which said second branch metric generating step responds.

19. A method as claimed in claim 16 wherein:

each phase estimate value conveys first and second convolutionally encoded symbols;

for one of said phase estimate values, said second branch metric generating step generates a value describing the likelihood that said first symbol exhibits a predetermined polarity; and

said second branch metric generating step comprises the step of compensating said first symbol likelihood value to null out influence of said second symbol.

20. A method as claimed in claim 19 wherein:

said first branch metric generating step generates a value describing the likelihood that said first symbol exhibits said predetermined polarity; and

said first branch metric generating step is configured so that said first branch metric likelihood value is influenced by said second symbol.

21. A method as claimed in claim 19 wherein:

said likelihood value approximately equals an average of a first chance value and a second chance value;

said first chance value represents the likelihood that said first symbol exhibits said predetermined polarity given said one phase estimate value and assuming a priori knowledge that said second symbol exhibits said predetermined polarity; and

said second chance value represents the likelihood that said first symbol exhibits said predetermined polarity given said one phase estimate value and assuming a priori knowledge that said second symbol exhibits a polarity opposite to said predetermined polarity.

22. A method as claimed in claim 19 wherein:

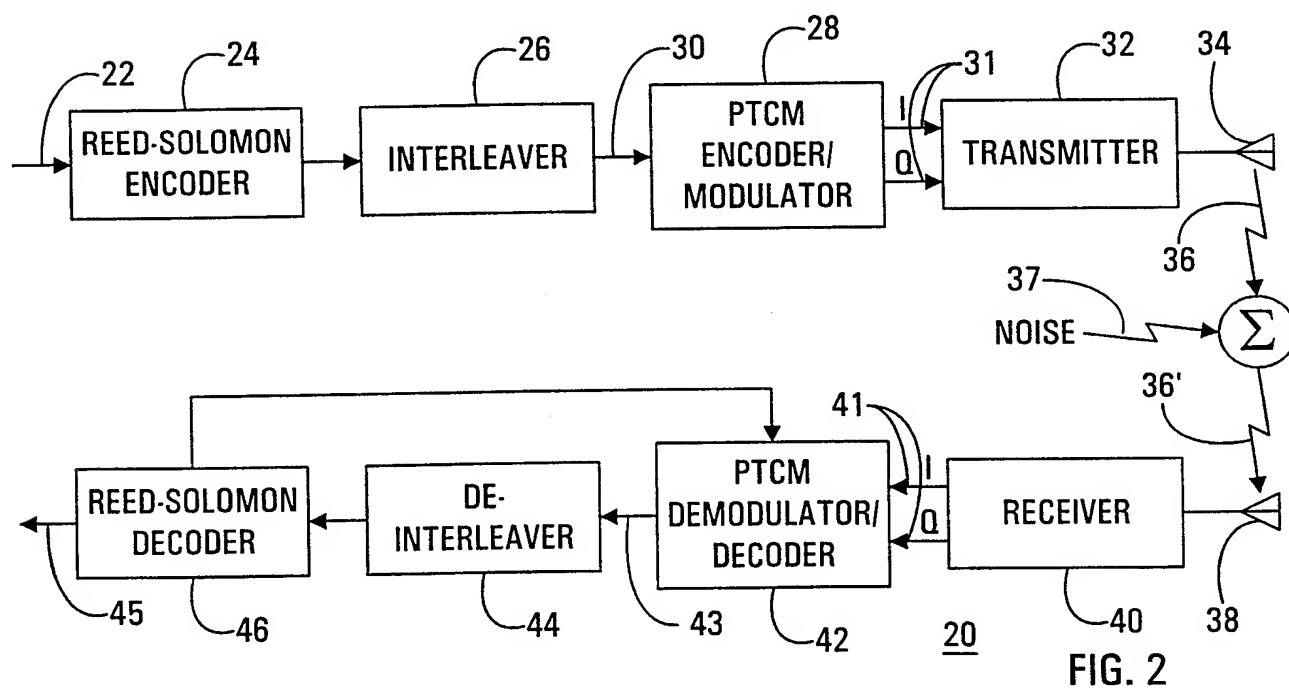
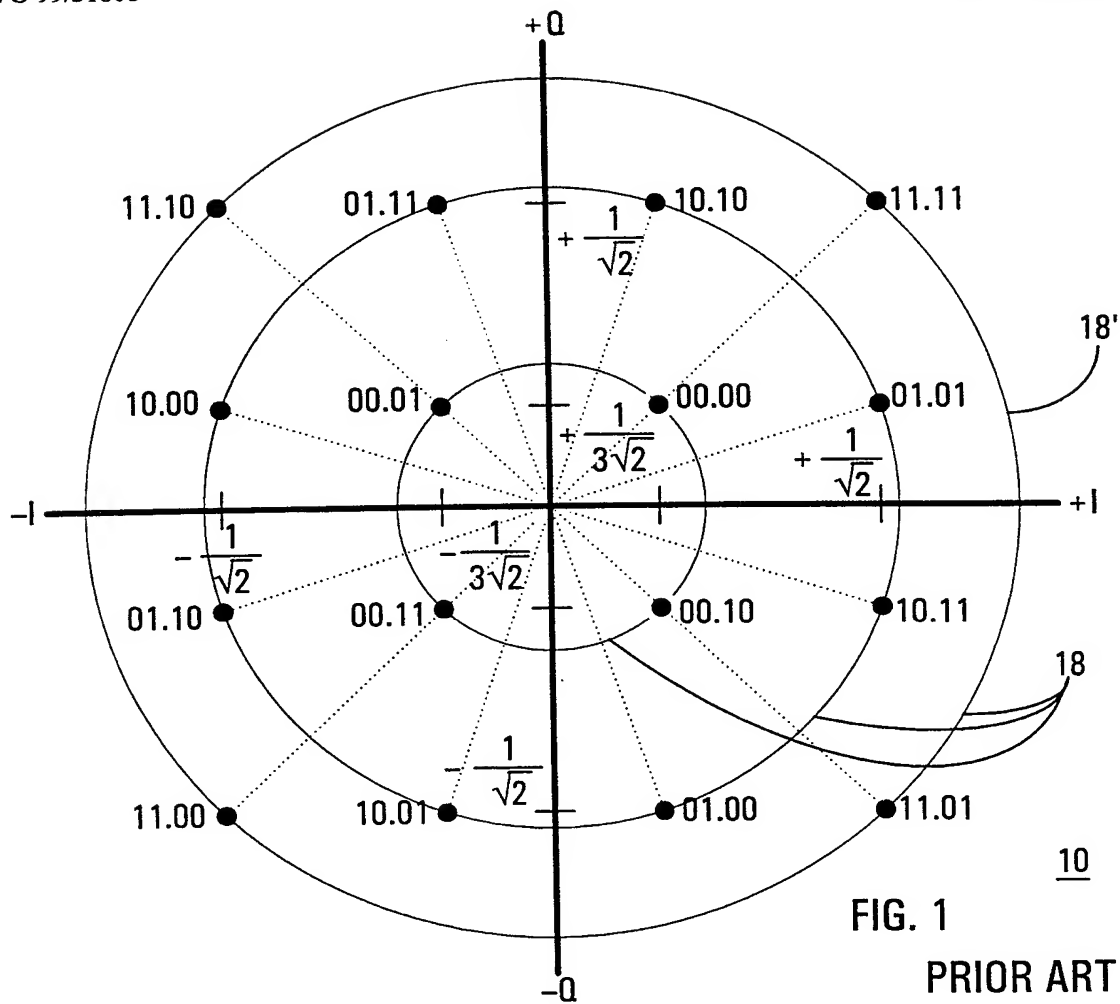
for said one phase estimate value, said second branch metric generating step generates a value describing the likelihood that said second symbol exhibits said predetermined polarity; and

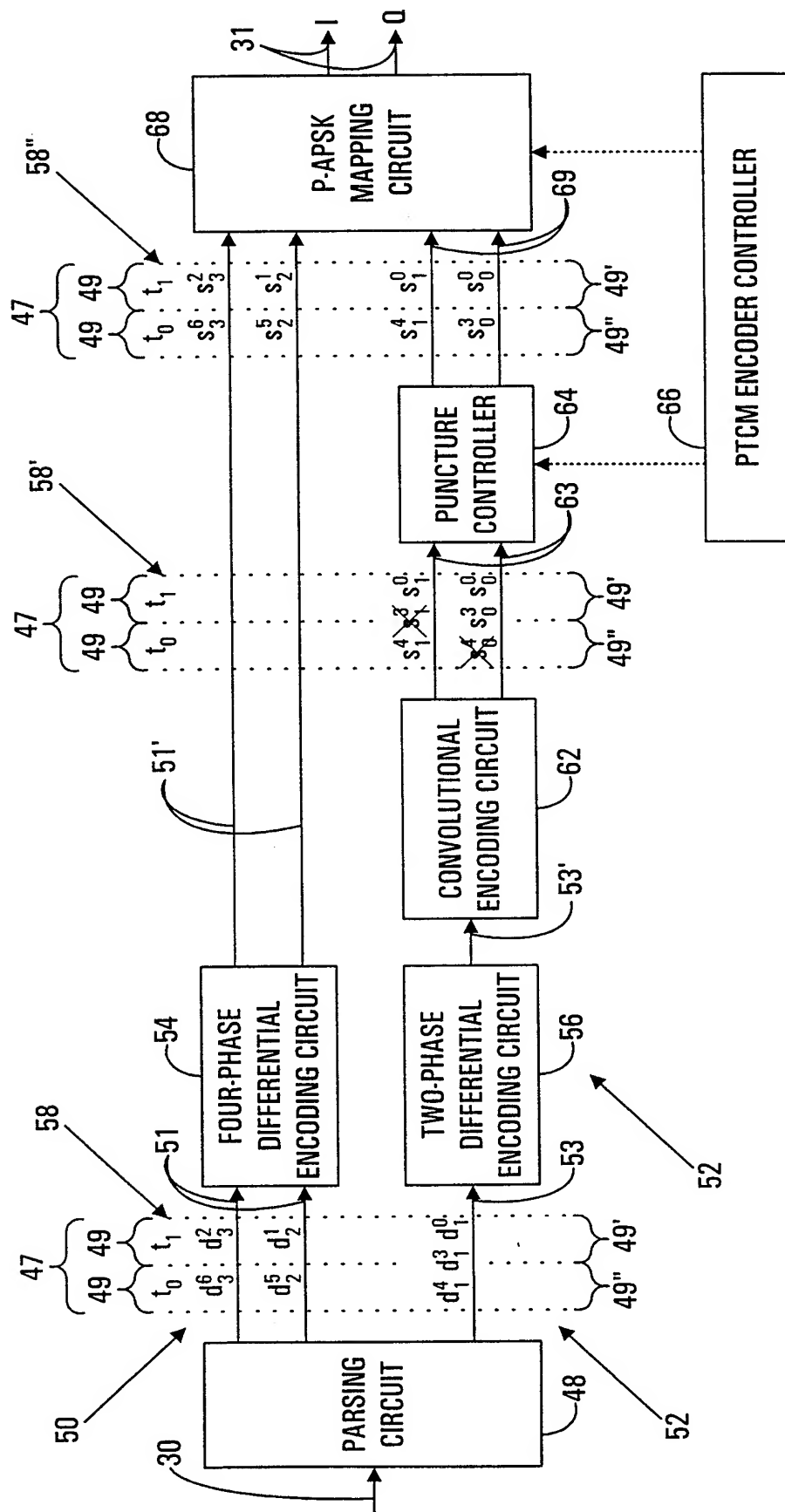
said second branch metric generating step comprises the step of compensating said second symbol likelihood value to null out influence of said first symbol.

23. A method as claimed in claim 15 wherein:

said erasure value producing step is performed in a programmable depuncture circuit; and

said method additionally comprises the step of programming said depuncture circuit with different data sets, said different data sets being configured to control depuncturing for different code rates.





28 FIG. 3

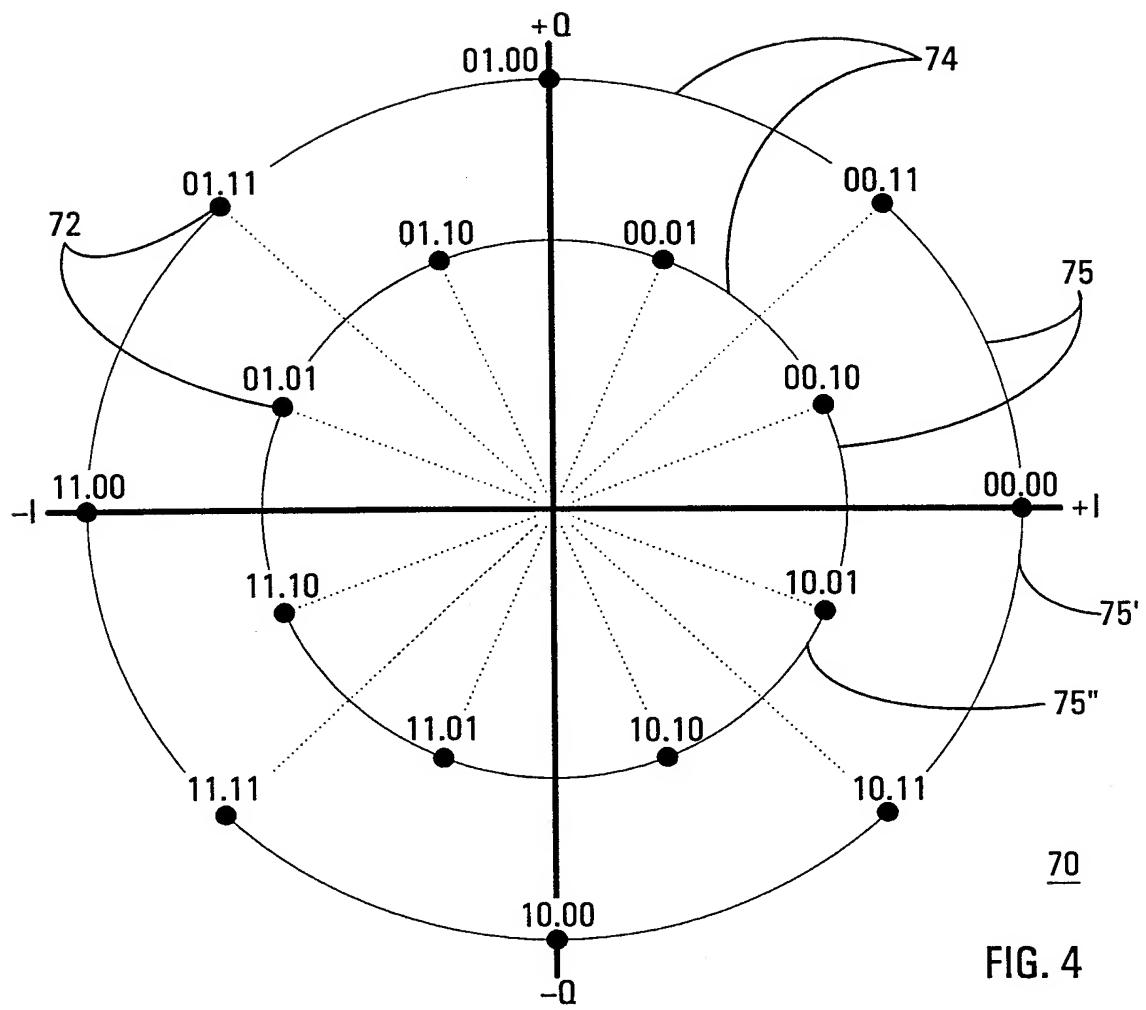
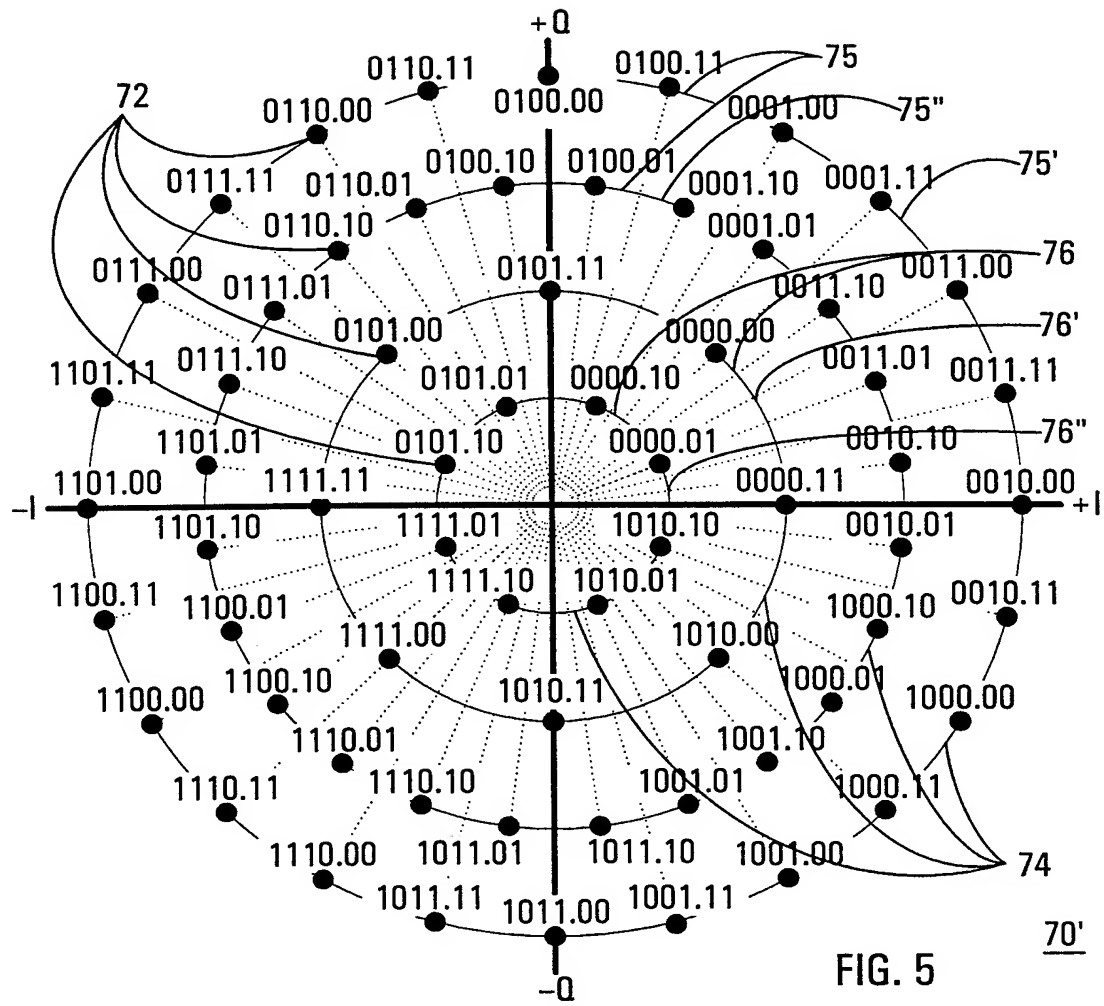


FIG. 4



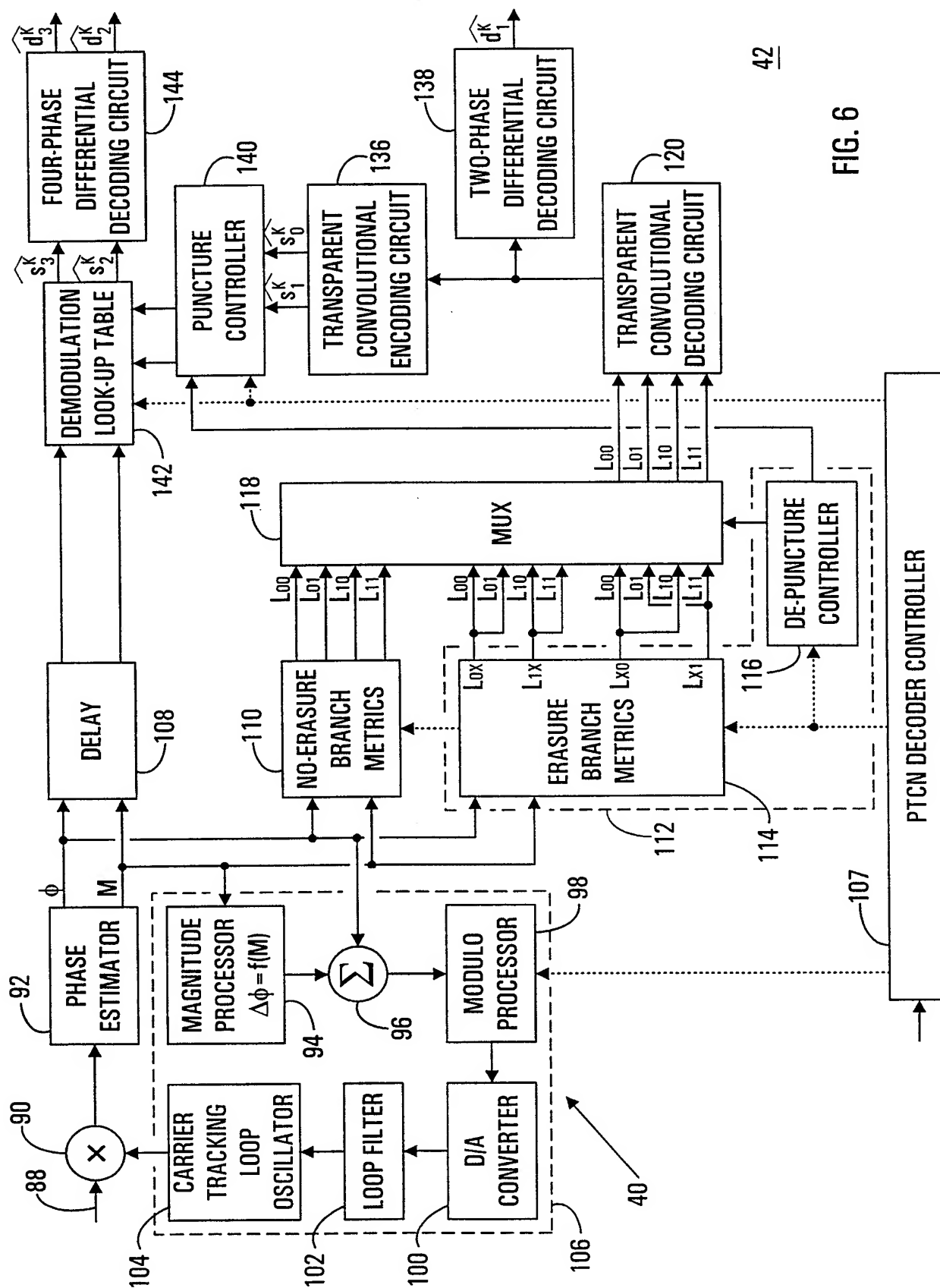


FIG. 6

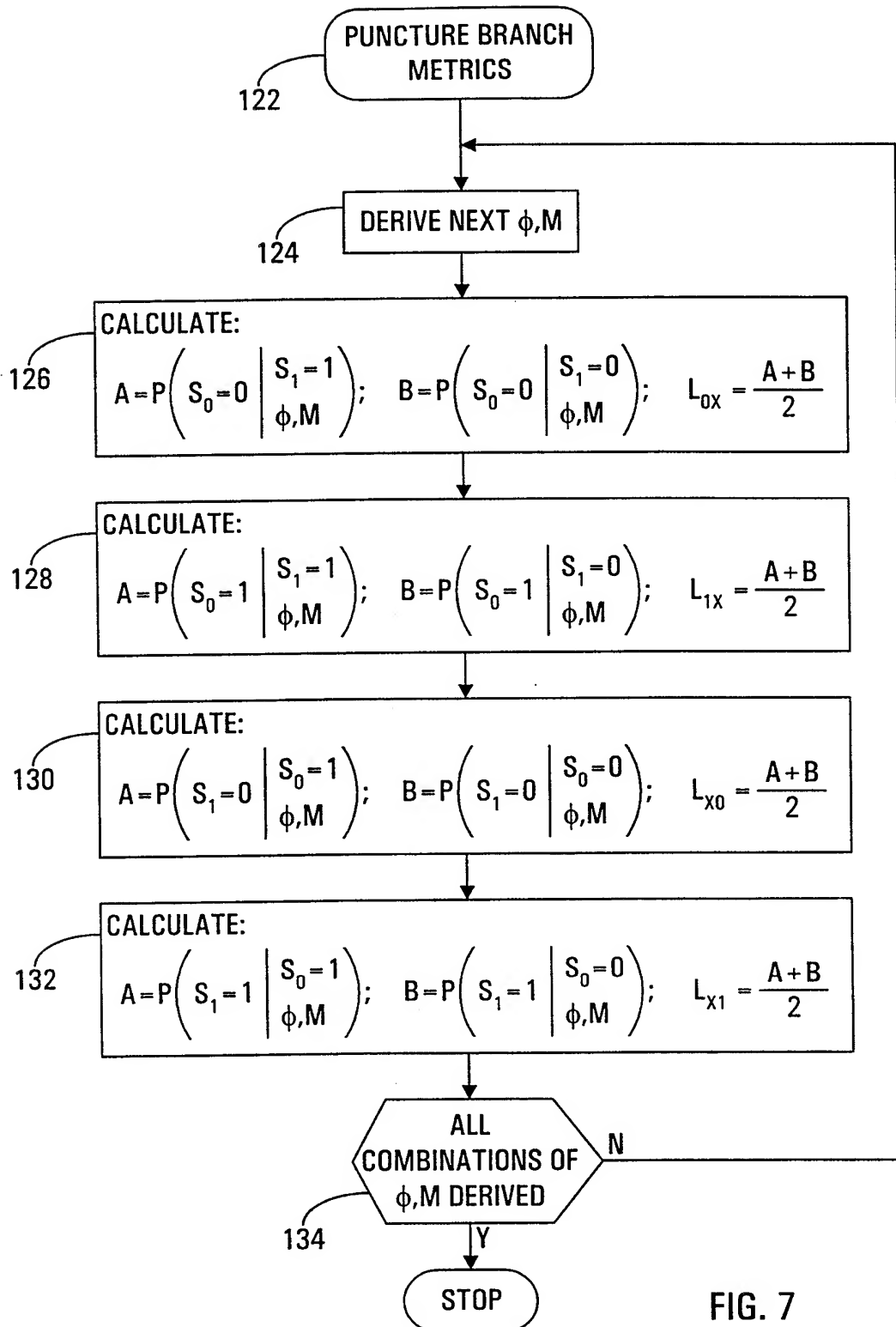


FIG. 7

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/26777

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : H03M 13/12

US CL : 375/341, 262, 265; 371/43.2

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 375/162, 262, 265, 340, 341; 371/43.1, 43.2, 43.4, 43.6, 43.7, 43.8

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS (phase estimator, convolutional decoder, and depuncture)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,668,820 A (RAMESH et al.) 16 September 1997, col. 4, lines 27-35 and col. 7, lines 31-46.	1, 11, 15, and 23
X, P	US 5,832,001 A (CHOI) 03 November 1998, col. 2, lines 37-46.	1, 11, 15, and 23
A	US 5,111,484 A (KARABINIS) 05 May 1992, col. 3, lines 35-52.	1 and 15
A	US 5,469,452 A (ZEHAVI) 21 November 1995, col. 11, lines 9-64.	1-23



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents:	*T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
A document defining the general state of the art which is not considered to be of particular relevance	*X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
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L document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	*&* document member of the same patent family
O document referring to an oral disclosure, use, exhibition or other means	
P document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

10 FEBRUARY 1999

Date of mailing of the international search report

01 APR 1999

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